United States Patent [19]

Warner

[11] **Patent Number: 4,669,530**

[45] **Date of Patent: Jun. 2, 1987**

[54] **HEAT EXCHANGER METHOD AND APPARATUS**

[75] Inventor: **Donald F. Warner**, Latham, N.Y.

[73] Assignee: **Heat Exchanger Industries, Inc.**, Latham, N.Y.

[21] Appl. No.: **810,557**

[22] Filed: **Dec. 19, 1985**

Related U.S. Application Data

[60] Division of Ser. No. 671,494, Nov. 14, 1984, Pat. No. 4,577,380, which is a division of Ser. No. 406,774, Aug. 10, 1982, Pat. No. 4,487,139, which is a continuation-in-part of Ser. No. 252,297, Apr. 9, 1981, abandoned, and a continuation-in-part of Ser. No. 081,789, Oct. 4, 1979, abandoned.

[51] **Int. Cl.**[4] **F28F 13/18**; F28B 1/00

[52] **U.S. Cl.** **165/1**; 165/111; 165/133; 165/145; 165/909; 165/180

[58] **Field of Search** 165/134.1, 133, 145, 165/909, 921, 180, 111

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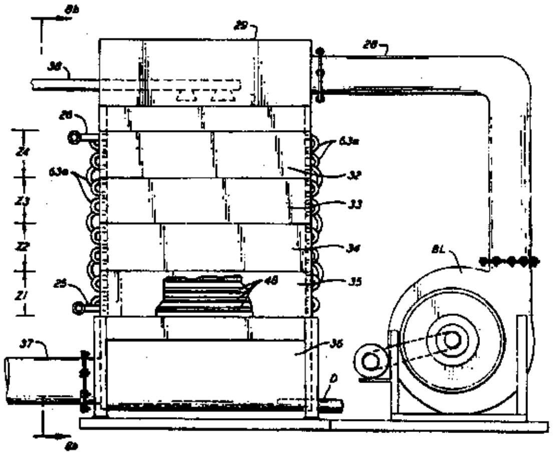
Primary Examiner—Albert W. Davis, Jr.
Attorney, Agent, or Firm—Richard G. Stephens

[57] **ABSTRACT**

An exhaust gas containing sulfur trioxide is passed through a first heat exchanger which cools the gas to a temperature which is above the sulfur trioxide dewpoint, so that condensation of sulfur trioxide does not occur in the first heat exchanger, but below a material limit operating temperature of a second heat exchanger, which further cools the gas below the sulfur trioxide dewpoint, whereby the first heat exchanger is protected against corrosion and the second heat exchanger is protected against thermal damage.

5 Claims, 26 Drawing Figures



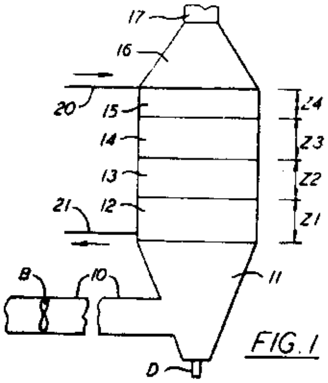


FIG. 1

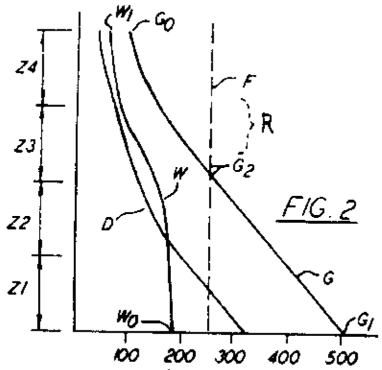


FIG. 2

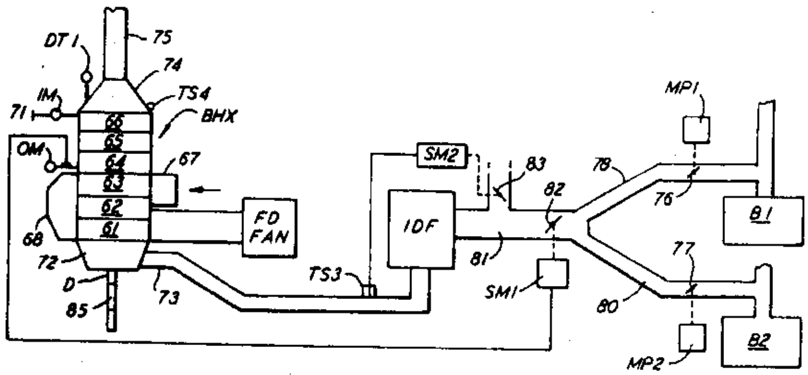


FIG. 6

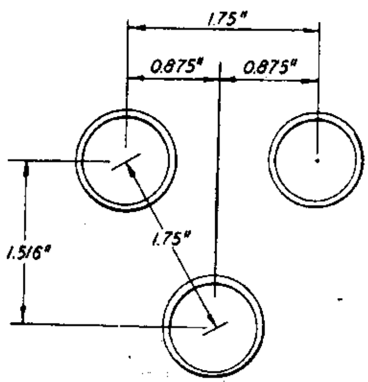


FIG. 4C

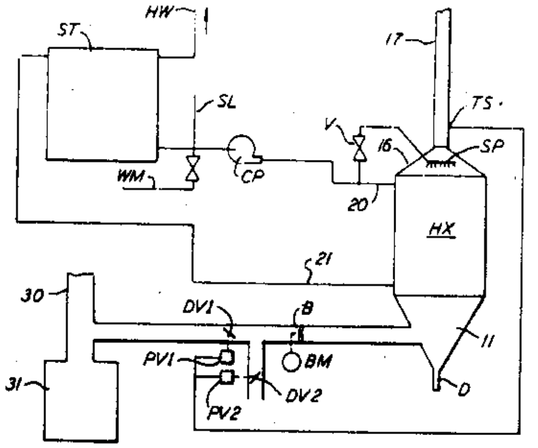


FIG. 3a

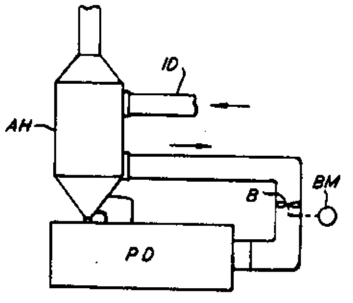


FIG. 3b

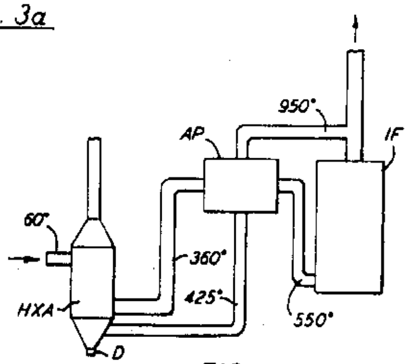


FIG. 3c

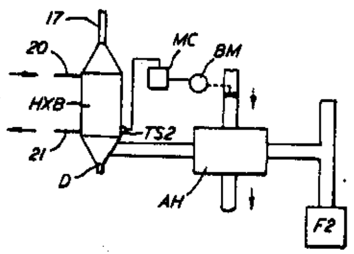


FIG. 3d

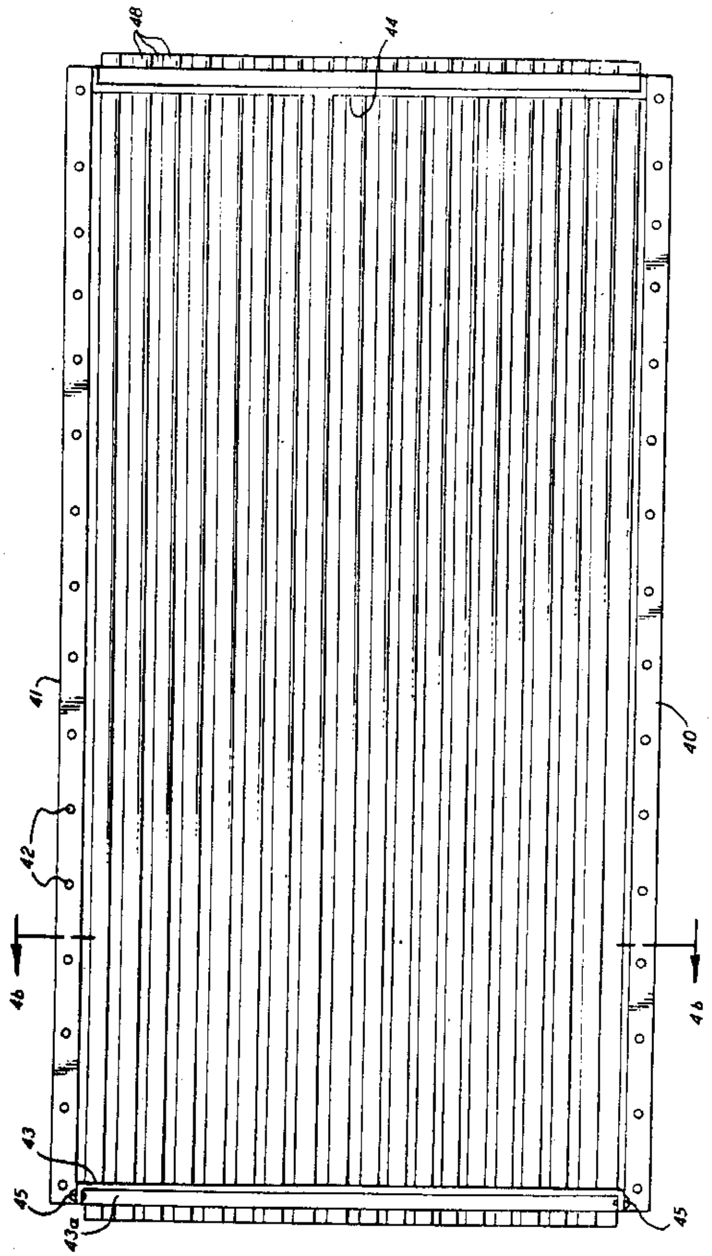
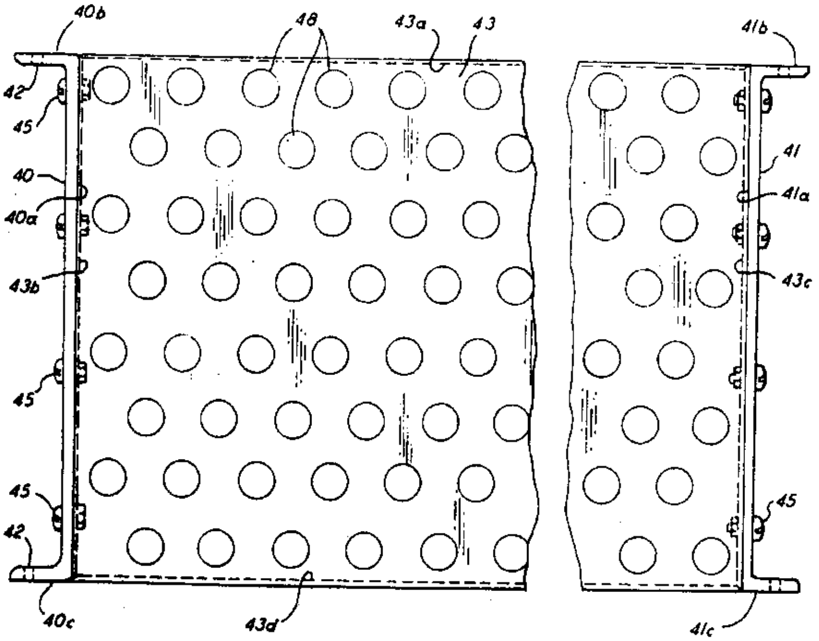


FIG. 4a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43a
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41b
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42
40c
43d
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41c

FIG. 4b

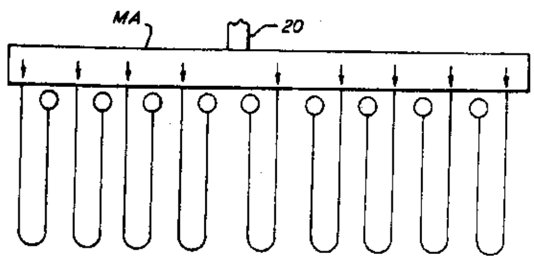
MA
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FIG. 4d

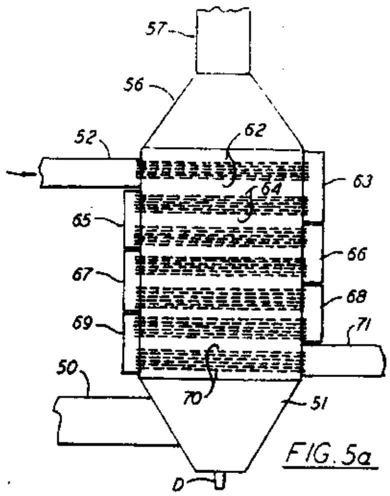


FIG. 5a

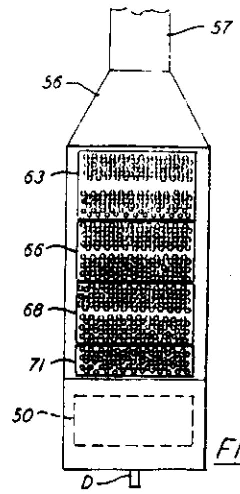


FIG. 5b

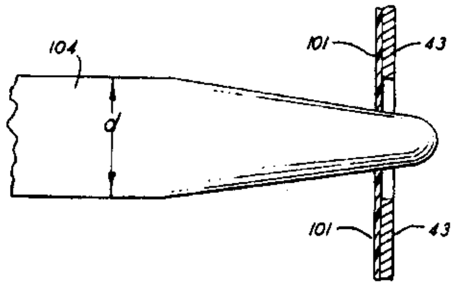


FIG. 7a

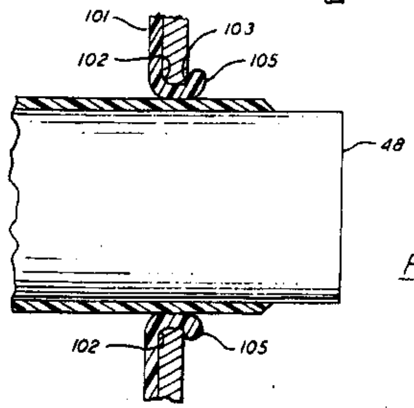
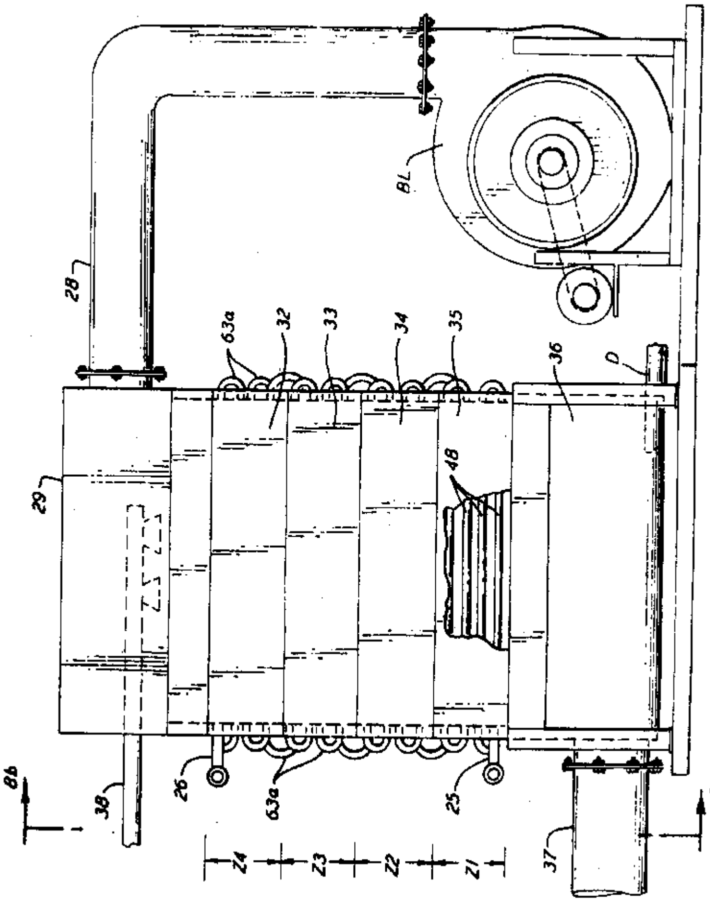


FIG. 7b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32
33
34
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26
63a
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8b
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Z4
Z3
Z2
Z1

FIG. 8a

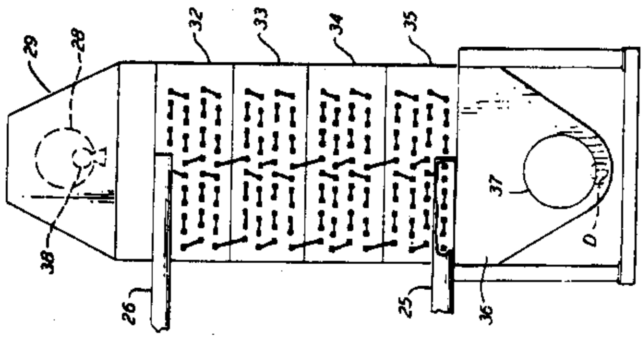
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FIG. 8b

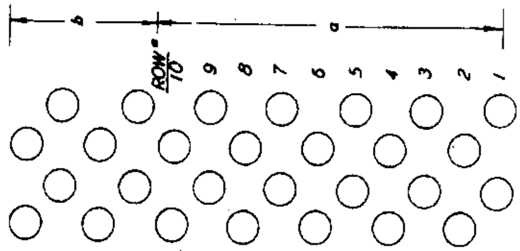


FIG. 9

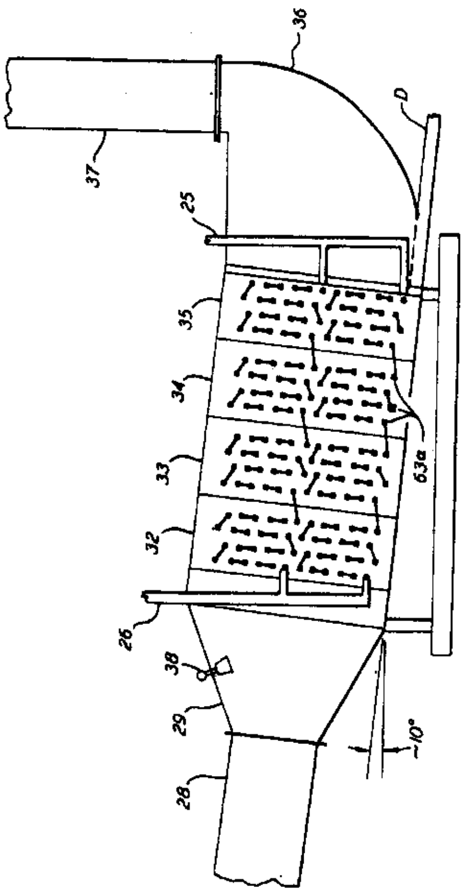
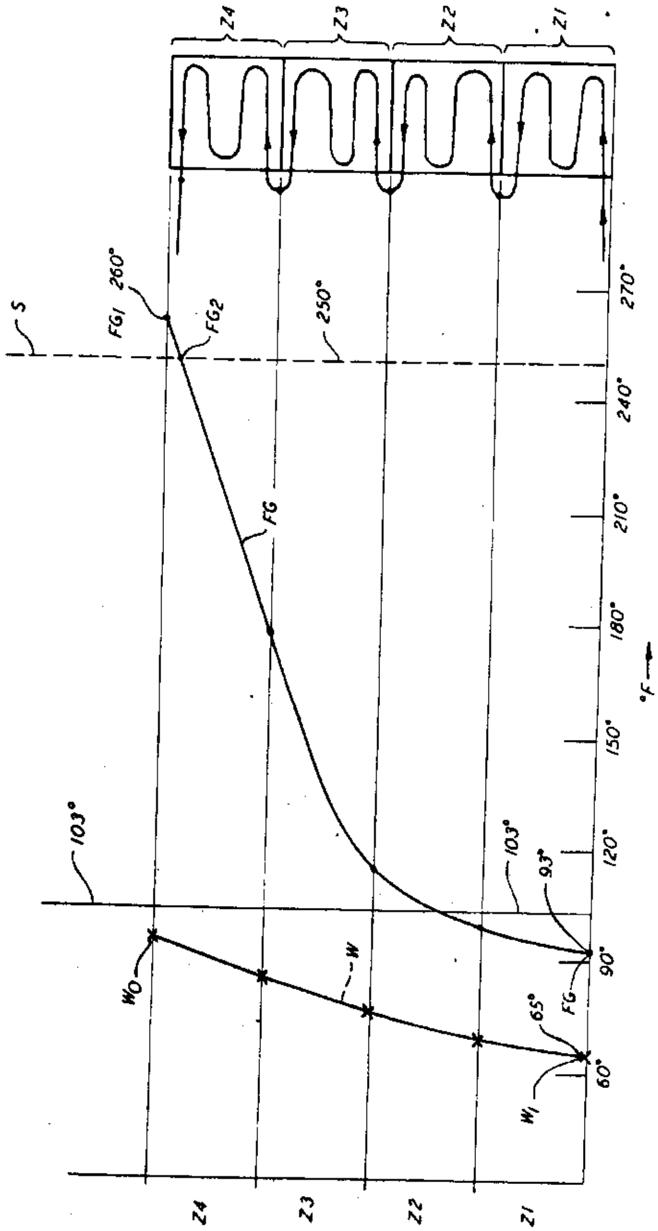


FIG. 8c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Z2
Z1
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260°
FG2
250°
S
270°
240°
210°
180°
150°
120°
90°
60°
FG
103°
103°
93°
W
WO
65°
FG
W1
°F
Z4
Z3
Z2
Z1

FIG. 10

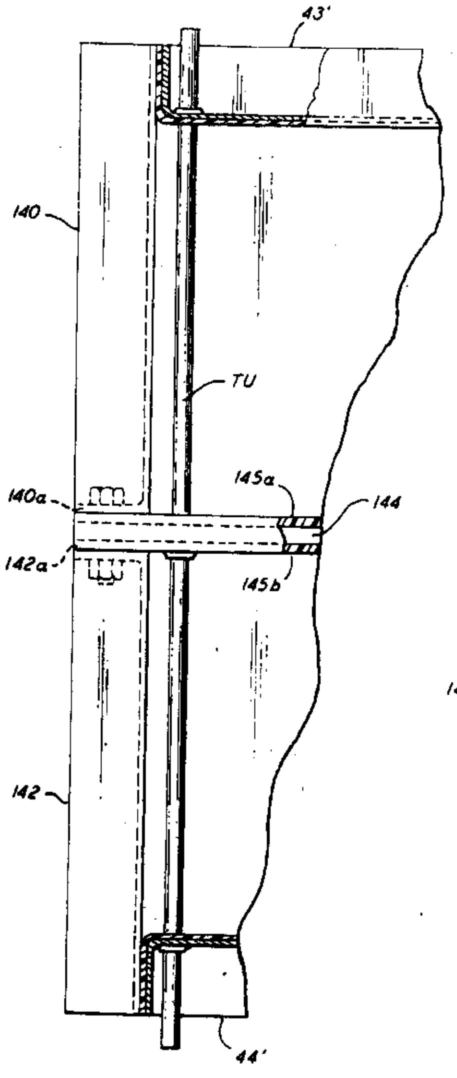

FIG. 11a

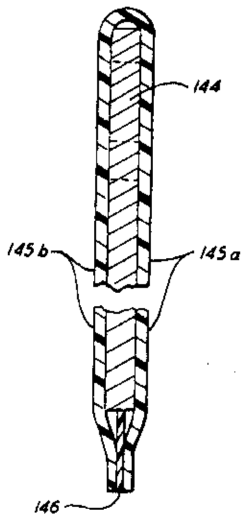

FIG. 11b

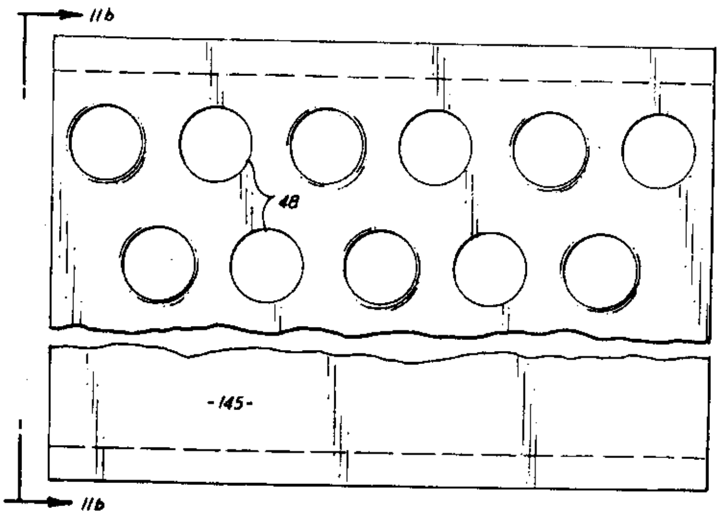

FIG. 11d

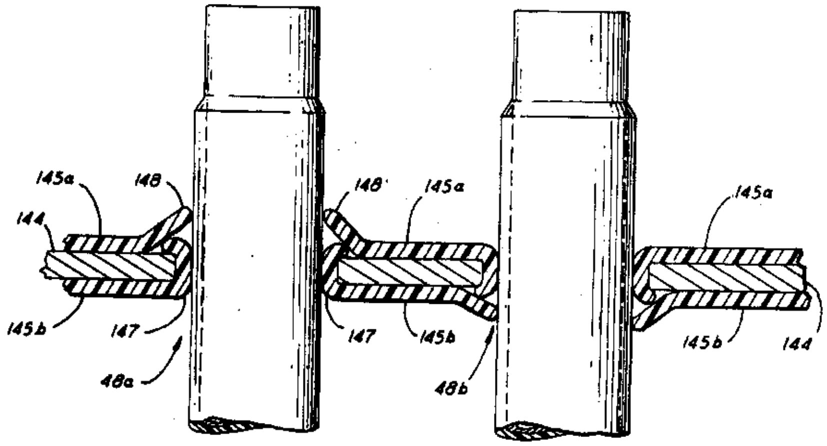

FIG. 11c

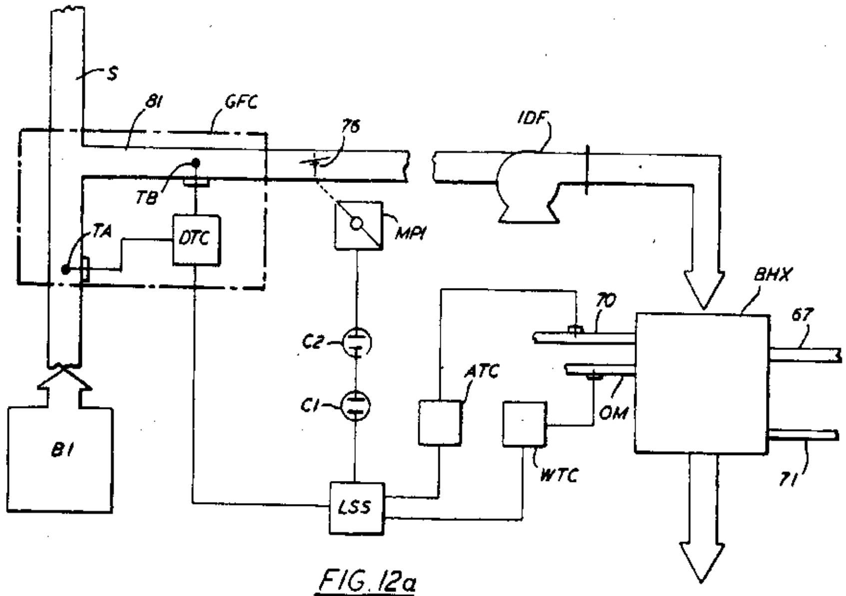

FIG. 12a

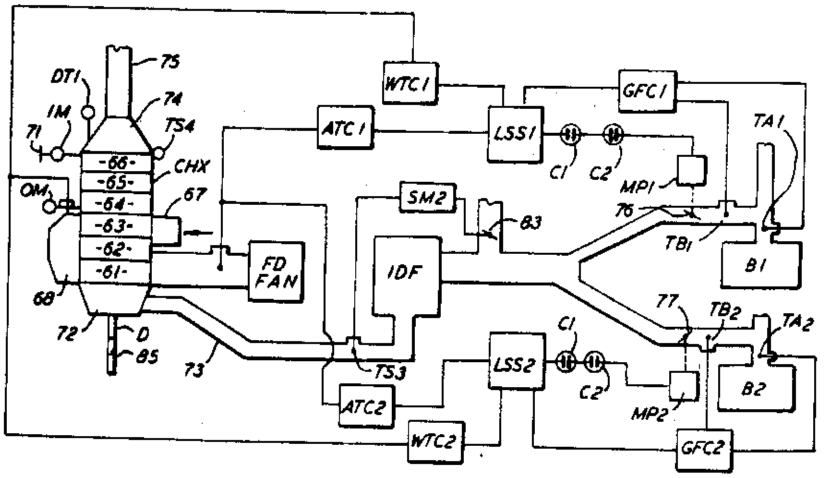

FIG. 12b

HEAT EXCHANGER METHOD AND APPARATUS

This application is a division of my copending Application Ser. No. 671,494 filed Nov. 14, 1984 now U.S. Pat. No. 4,577,380 granted Mar. 25, 1986, which was a division of Application Ser. No. 406,774 filed Aug. 10, 1982 now U.S. Pat. No. 4,487,139 granted Dec. 11, 1984, which was a continuation-in-part of Application Ser. No. 252,297 filed Apr. 9, 1981 now abandoned and a continuation-in-part of Application Ser. No. 81,789 filed Oct. 4, 1979 now abandoned.

My invention relates to exhaust gas treatment method and apparatus, and more particularly, to improved method and apparatus useful not only for recovering large amounts of heat from various industrial exhaust gases, but also for simultaneously removing substantial amounts of particulate matter and corrosive products of combustion from such exhaust gases, thereby to reduce air pollution from stack emissions. The invention is particularly directed toward such treatment of sulfur-containing exhaust gases, such as those typically produced by burning oil or coal in furnaces, though it will become apparent that the invention will be useful in a wide variety of other applications. A primary object of the invention is to provide method and apparatus which are useful for recovering a substantially larger percentage of the heat contained in an exhaust gas than that recovered in typical prior systems, which has very important economic implications, due to the high costs of fuels. Another important object of the invention is to provide method and apparatus which are useful for removing substantial amounts of particulate matter and corrosive products of combustion from exhaust gases, thereby decreasing pollution. Natural gas, #2 fuel oil, #6 fuel oil, and coal, generally ranked in that order, produce flue gases containing increasing amounts of sulfur dioxide and sulfur trioxide, and particulate matter, such as soot and silica products. One object of the invention is to provide method and apparatus which is useful in connection with flue gases produced by any of those fuels.

In many applications it is desirable that waste heat be used to pre-heat a liquid, such as boiler make-up water, or industrial process water as examples, while in many other applications it may be preferred that waste heat be used to preheat a gas, such as air, and in some applications to heat both a liquid and a gas. Another object of the invention is to provide a method which lends itself to preheating of either a liquid or a gas or both a liquid and a gas, and to provide apparatuses which preheat liquid or a gas or both a liquid and a gas.

A very important object of the present invention is to provide method and apparatus which is rugged and reliable, and useful over long periods of time with minimum attention, and minimum requirements for "downtime" for cleaning or repair.

Another more specific object of the invention is to provide a heat exchanger which functions as a self-cleaning gas scrubber as well as recovering increased amounts of heat from an exhaust gas.

It long has been known that the thermal efficiency of a plant or process can be increased by recovering some of the heat energy containin the exhaust gas from a boiler furnace or the like. Flue gas commonly is directed through boiler economizers to preheat boiler feedwater, and commonly directed through air preheaters to preheat furnace combustion air, in each case pro-

viding some increase in thermal efficiency. The amount of heat which it has been possible to recover from flue gas ordinarily has been quite limited, due to serious corrosion problems which otherwise result. Combustion of oil, coal or natural gas produces flue gas having substantial moisture, sulfur dioxide, sulfur trioxide, and particulate matter in the cases of oil and coal. If a heat exchanger intended to recover heat from flue gas condenses appreciable amounts of sulfur trioxide, sulfuric acid is formed, resulting in severe corrosion. The condensed sulfur product can readily ruin usual economizers and air preheaters, and the exhaust stacks associated with them. Thus prior art systems intended to recover heat from flue gas traditionally have been operated with flue gas temperatures scrupulously maintained high enough to avoid condensation of sulfur products.

The temperature at and below which condensation will occur for a flue gas not containing any sulfur oxides, i.e., the dew point due to water vapor only, is usually within the range of 100° F. to 130° F., depending on the partial pressure of water vapor. But the presence of sulfur trioxide even in small amounts, such as 5 to 100 parts per million, drastically increases the temperature at which condensation will occur, far above that for water vapor only. For example, 50 to 100 parts per million of SO_3 may raise the dew point temperature to values such as 250° F. to 280° F., respectfully. Thus it has been usual practice to make absolutely certain that flue gas is not cooled below a temperature of the order of 300° F., in order to avoid condensation and corrosion. Such operation inherently results in an undesirably small portion of the sensible heat energy being extracted from the flue gas, and in absolutely no recovery of any latent heat energy contained in the flue gas. One concept of the present invention is to provide method and apparatus for recovering heat from a potentially corrosive exhaust gas, such as flue gas, in a manner directly contrary to prior art practices, using a heat exchanger which continuously operates in a "water-condensing" mode, allowing substantial amounts of latent heat, as well as more sensible heat, to be recovered from the exhaust gas. The term "water condensing" is meant to mean that the temperature of a large percentage (and ideally all) of the exhaust gas is lowered not only below the sulfuric acid condensation or saturation temperature, but even below the saturation temperature of water at the applicable pressure, i.e. below the dew point, e.g. 120° F., for water vapor only. In a typical operation of the invention where absolute pressure of the flue gas within a heat exchanger is of the order of 0.2 to 5 inches of water, the temperature of large portions of the flue gas is lowered at least below 120° F. to a temperature of say 75° F. to 100° F., by passing the flue gas through a heat exchanger scrubber unit. The unit continuously condenses a large amount of water from the flue gas, as well as condensing sulfuric acid. Parts within the heat exchanger-scrubber unit which would otherwise be exposed to the corrosive condensate are appropriately lined or coated with corrosion-resistant materials, e.g. a fluoroplastic such as "Teflon" (trademark of E. I. duPont de Nemours & Co., Inc.) to prevent corrosion.

When prior art waste heat recovery systems have been operated with flue gas temperatures (e.g. 250° F.) too near the SO_3 condensation temperature, whether by accident, or during startup, or in attempts to improve system thermal efficiency, the occasional condensation of SO_3 tends to produce very strong or concentrated

sulfuric acid. The sulfuric acid, is extremely corrosive and can rapidly destroy an ordinary heat exchanger. The volume of sulfuric acid which can be condensed is small, but sufficient to keep heat exchanger surfaces slightly moist. However, if one not only ignores prior art practice, but operates in direct contradiction thereto, and further lowers the flue gas temperature to a level markedly below the SO_3 condensation temperature, to operate in the water condensing mode of the invention, the production of large amounts of water tends to substantially dilute the condensed sulfuric acid, making the resultant overall condensate much less corrosive, and less likely to damage system parts. Thus operation in the water condensing mode of the invention has an important tendency to lessen corrosion of system parts, as well as allowing large amounts of latent heat energy to be recovered. Such dilution of the sulfuric acid does not wholly eliminate corrosion, however, so that it remains necessary to appropriately line or coat various surfaces within the heat exchanger-scrubber unit with protective materials.

I have discovered that if I pass flue gas through heat exchanger apparatus which is operating in the water condensing mode, not only can much more heat energy be extracted from the flue gas, and not only can the condensate be made less corrosive, but in addition, large amounts of particulate matter and SO_3 simultaneously can be removed from the flue gas, thereby considerably reducing air pollution. I have observed that if flue gas is cooled slightly below the sulfuric acid condensation temperature, and if the flue gas contains a substantial amount of particulate matter, a soggy mass of sulfuric acid combined with particulate matter often will rapidly build up on heat exchange surfaces, and indeed the buildup can clog the heat exchanger in a matter of a few hours. But if the system is operated in the water condensing mode in accordance with the present invention, the production of copious amounts of water continuously washes away sulfuric acid and particulate matter, preventing buildup of the soggy mass. In simple terms, the water condensing mode of operation forms a "rain" within the heat exchanger. The "rain" not only entraps particles in the flue gas as it falls, but it also washes away, down to a drain, particles which have lightly stuck to the wetted surfaces. Thus advantages akin to those of gas scrubbing are obtained without a need for the continuous supply of water required by most gas scrubbers, and with no need for moving parts.

Yet, even in addition to recovering large amounts of latent heat energy, greatly diluting and washing away sulfuric acid to minimize corrosion problems, and removing substantial amounts of particulate matter from exhaust gases such as flue gas, operation in the "water condensing" mode also enhances the heat transfer coefficient of heat exchanger units used to practice the invention. Heavy condensation made to occur near the top of the heat exchanger unit runs or rains downwardly, maintaining heat exchange surfaces wetted in lower portions of the heat exchanger, even though condensation otherwise is not occurring on those surfaces.

Heat transfer is improved for several separate but related reasons. Heat transfer from the gas occurs better if a surface is wet from drop-wise condensation. Use of a fluoroplastic such as "Teflon" promotes dropwise condensation. Further, the constant rain within the heat exchanger keeps the tube surfaces clean, preventing the buildup of deposits which would decrease heat transfer.

Thus another object of the invention is to provide improved heat recovery apparatus having improved heat transfer.

While I have found various forms of fluoroplastics to provide very effective corrosion protection, and to have hydrophobic characteristics which cooperate with water vapor condensation to keep a water-condensing heat exchanger clean, currently available forms of those corrosion-protection materials have deformation, melting or destruction temperatures far below the temperatures of some flue gases from which it is desirable to extract waste heat. In accordance with another aspect of the present invention, I propose to operate a water-condensing heat-exchanger in cooperation with another heat exchanger of conventional type, which may be severely damaged if condensation takes place in it. The conventional heat exchanger can initially cool an exhaust gas such as flue gas down to a temperature which is low enough that it will not damage the corrosion-protection linings of the water-vapor condensing heat exchanger, yet high enough that sulfur trioxide cannot condense in the conventional heat exchanger so as to damage it. Thus some added objects of the invention are to provide improved heat recovery systems which are useful with exhaust gases having a wide range of temperatures.

Some added objects of the invention are to provide heat exchanger modules suitable for use in the mentioned water-condensing mode which can be readily combined as needed to suit a wide variety of different flow rate, temperature and heat transfer requirements. Another object of the invention is to provide a satisfactory method of constucting and assembling a water-condensing heat exchanger system.

An important further object of the invention is to provide improved condensing heat exchanger systems having improved heat transfer coefficients, so that increased amounts of heat can be recovered per unit area of heat transfer surface. More specifically, one object of the invention is to provide condensing heat exchangers having markedly improved heat transfer by reason of the exhaust gas being forced vertically downwardly, between and around horizontally-extending cylindrical tubes which carry the fluid (water or air) being heated, with condensation of water vapor from the exhaust gas occurring only adjacent a lowermost group of the tubes. Another object of the invention is to provide a condensing heat exchanger having such improved heat transfer in which effective removal of particulates also occurs.

Another object of the invention is to provide a condensing heat exchanger in which exhaust gas flow proceeds substantially horizontally, which enables one to provide heat exchangers having modest heights.

Another object of the invention is to provide an improved exhaust gas scrubbing system requiring less water.

Other objects of the invention will in part be obvious and will in part appear hereinafter.

The invention accordingly comprises the several steps and the relation of one or more of such steps with respect to each of the others, and the apparatus embodying features of construction, combination of elements and arrangement of parts which are adapted to effect such steps, all as exemplified in the following detailed disclosure, and the scope of the invention will be indicated in the claims.

For a fuller understanding of the nature and objects of the invention reference should be had to the following detailed description taken in connection with the accompanying drawings, in which:

FIG. 1 is a diagram of a heat exchanger system useful in understanding some basic principles of the present invention.

FIG. 2 is a set of graphs useful in understanding principles of one method of the present invention.

FIG. 3*a* is a schematic diagram of one form of water heating system according to the invention.

FIG. 3*b* is a diagram illustrating use of the invention in connection with a direct-fired paper dryer to save heat energy and remove particulate matter from the exhaust gas from the paper dryer.

FIGS. 3*c* and 3*d* each is a diagram illustrating a use of the water-condensing heat exchanger of the present invention together with a prior art air preheater.

FIG. 4*a* is a plan view of an exemplary heat exchange module in accordance with the invention.

FIG. 4*b* is a partial cross-section elevational view taken at lines 4*b*—4*b* in FIG. 4*a*.

FIG. 4*c* is a diagram useful for understanding the heat exchange tube spacing in a preferred embodiment of the invention.

FIG. 4*d* is a diagram illustrating one form of water manifolding which may be used in connection with the invention.

FIGS. 5*a* and 5*b* are front elevation and side elevation views of an exemplary air heat form of water-vapor condensing heat exchanger.

FIG. 6 illustrates an exemplary heat recovery system utilizing a heat exchanger which heats both air and water from boiler flue gas.

FIGS. 7*a* and 7*b* are partial cross-section views useful for understanding a method of assembly according to the present invention and the nature of tube-to-tube sheet seals provided by use of such a method.

FIGS. 8*a* and 8*b* are side view and end view diagrams of a gas downflow version of the condensing heat exchanger of the invention, and FIG. 8*c* is a side view of a horizontal gas flow version of the invention.

FIG. 9 is a diagram helpful in understanding the function of the improved downflow model heat exchanger of FIGS. 8*a* and 8*b*.

FIG. 10 is a set of graphs useful in understanding principles of the gas downflow heat exchanger of FIGS. 8*a* and 8*b*.

FIG. 11*a* is a partial plan view illustrating a heat exchanger module incorporating an intermediate tube support.

FIG. 11*b* is a sectional view of an intermediate tube support taken at lines 11*b*—11*b* in FIG. 11*d*.

FIG. 11*c* is a sectional view illustrating details of the intermediate tube support.

FIG. 11*d* is a side view illustrating the intermediate tube support sheet.

FIG. 12*a* is a diagram showing one alternative flue gas flow control system for use with a single boiler.

FIG. 12*b* is a further alternative flue gas flow control system for a multiple boiler system.

Some major principles of the present invention can be best understood by initial reference to FIGS. 1 and 2. In FIG. 1 duct 10 conducts hot exhaust gas, such as flue gas drawn from a boiler stock (not shown) by blower B, to a bottom plenum or chamber 11. The flue gas passes upwardly through one or more heat exchange units, such as the four units indicated at 12,13,14 and 15, thence into an upper plenum or chamber 16 and out a stack 17. In typical operations the flue gas velocity is arranged to be 10–40 feet per second within the heat exchange units, and a gas pressure drop of the order of one and a half to two inches of water is arranged to occur across the heat exchange units. A fluid to be heated, which typdically will be water or air, is shown introduced into the uppermost heat exchange unit at 20, understood to flow downwardly through successive ones of the heat exchange units, and to exit at 21. For simplicity of explanation it initially will be assumed that water is to be heated, and that the hot exhaust gas is flue gas from a boiler.

It will be apparent that the flue gas will be cooled to some extent as it travels upwardly through the unit, and that the water will be heated to some extent as it travels downwardly through the unit. To facilitate explanation, the range of elevations within which significant gas cooling and water heating occur is shown divided into four zones Z1 to Z4. The four zones are shown for simplicity of explanation as corresponding to the vertical ranges of the four heat recovery units.

FIG. 2 illustrates the variations of flue gas and water temperatures in typical practice of the invention to heat water, with the temperatures plotted against vertical elevation. Thus the temperture of flue gas falls from an assumed input temperature G_1 of 500° F. at the bottom of the heat exchanger system to an assumed output temperature G_0 of 90° F. at the top of the heat exchanger system as the flue gas travels upwardly through the heat exchanger, as indicated by curve G. The gas temperature plot in FIG. 2 should be understood to be approximate, and in general to depict for any elevation the lowest temperature to which substantial portions of the gas are lowered at that elevation. At any elevation above the lowermost row of tubes there are temperature gradients, of course, and the average temperature, if averaged over the entire cross-sectional area of the heat exchanger at a given elevation, will be above that plotted as curve G. Viewed in another way, at a given elevation, such as that bounding zones Z2 and Z3, some portions of the flue gas, such as portions near or on a tube may have the temperature G_2 at which sulfuric acid is forming, while other portions of the gas at the same elevation but at greater distances from any tube may be hotter and not yet experiencing condensation. Simultaneously, water assumed to have an input temperature W_1 of 55° F. at the top of the heat exchanger is heated to an output temperature W_0 of 180° F. by the time it reaches the bottom of the heat exchanger, as indicated by curve W. The ordinate scale in FIG. 1 is shown divided into the four zones Z1 to Z4. A vertical dashed line F at 250° F. indicates a typical temperature G_2 at which sulfuric acid forms in typical flue gas obtained from burning No. 6 fuel oil. The prior art has taught that flue gas temperature always should be maintained amply above that level in order to avoid production of any sulfuric acid.

Following the flue gas temperature curve G for upward flue gas travel, it will be seen that the flue gas temperature drops from 500° F. at G_1 to 250° F. at G_2 as the gas passes through the two lower zones, Z1 and Z2. During that portion of its upward travel very little condensation is occurring from the gas, but sensible heat from the flue gas is being transferred to heat the water. More precisely, most of the gas in zones Z1 and Z2 is still too hot for sulfuric acid to condense, but some amounts of the gas in zones Z1 and Z2 will condense